CHAPTER 16

Maintenance of Structure

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CHAPTER 16

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Introduction

1 Other chapters of this publication cover the design of structures to resist predicted operational loads. In some cases these loads have been influenced by the intended life of the vessel, particularly where loads are cyclic, and in some cases allowance has been made for deterioration in service. Little reference has so far been made to the maintenance of structure so that it remains close to its design condition and so that the design assumptions remain valid. This chapter considers the various factors which contribute to the degradation of structural performance through a ship's life and the measures required to maintain or repair structure to an acceptable standard. These maintenance activities contribute to the through life cost of the vessel and so its loss of availability during repair periods. It is clear that the designer should take steps to reduce the maintenance load where it is practicable to do so, giving due consideration to life cycle costs as well as construction costs and performance requirements.

2 Ideally the structure should function in accordance with its original design requirements for the whole of its life without any interference; in practice, however, this is rarely possible except for the simplest of short life structures or those, such as reactor pressure vessels, which are inevitably inaccessible for survey and maintenance. The part of design which accounts for the requirements of optimising through life effectiveness is known as Availability-Reliability-Maintainability (ARM) modelling. This can be formalised for machinery and weapon systems, but for structures there is no formal method which it is appropriate to apply. What is required is an understanding that a ship's structure will always deteriorate in service due to normal wear and tear, corrosion and fatigue, and that to avoid unnecessary loss of operational time it must be easy to obtain access for survey, preservation and repair, and that neither process should need unconventional equipment or techniques.

3 The trade-off equation for optimising the extent of maintenance should have first cost and through life maintenance cost on one side and the value of operational time and of safety and reliability on the other. Theoretically, maintenance costs can be reduced by an increased first cost and these figures should be adjusted to the maximum operational value. However, it is virtually impossible to put a value on keeping a ship at sea especially as it is dependent on the total number of ships potentially available and the day to day need for ships at sea (much higher in wartime than in peacetime for instance). A quick maintenance turn round time is clearly of greater importance in a small navy than a large one because the marginal value of a single ship is greater. In practice these aspects can only be considered qualitatively, and the structural designer should provide a structure which is as simple, open and accessible as possible without requiring a *significant* increase in weight or size. Cost of additional structural material is small in relation to

the overall cost of the ship, and even to the labour cost of building the structure, as discussed by Chalmers (1986), and *should* not need so much justification.

Deterioration in Service

4 There are three root causes of deterioration of a ship's structure, the presence of a corrosive environment, that is seawater, the continual loading and unloading of the structural material, and rough usage. Salt water and air together will corrode unprotected structural steel rapidly and indeed can damage other materials severely as discussed in Chapter 5. Cyclic loading will cause fatigue failure in susceptible materials which include both steel and aluminium. Rough treatment can distort or sometimes tear metal structure and can delaminate fibre reinforced plastic (FRP) materials. These phenomena are also interactive, for example excessive corrosion will reduce strength and so increase the likelihood of fatigue and other damage, while abrasion can remove protective coatings and precipitate corrosion in metals and water ingress in FRP.

5 The most common reason for structure to deteriorate is corrosion. Ship structural steels are always prone to corrosion and, additionally, the marine environment is relatively severe compared to the environment of most land based structures. It is consequently of particular importance to design structures that are easy to protect or preserve from the effects of salt water and high humidity. The second most frequent cause of structural deterioration in service is fatigue which is covered in theoretical detail in Chapter 13. As will be apparent from that chapter, the most effective means of reducing fatigue damage is to design a ship with moderate average stresses and then to minimise stress concentrations by good attention to detail. To provide a structure that is resistant to rough handling there is little that the designer can do but to make it rugged and avoid very light scantlings. The following paragraphs discuss the requirements for survey and repair and then make recommendations for design measures that can be taken to improve the ARM aspects of a ship's structure.

Survey and Repair

6 All structure should be surveyed at regular intervals and the frequency of survey should be borne in mind during the design process. That is, for example, the designer should make allowance for the possible length that a fatigue crack could reach between surveys when preparing the details of stress concentrations. Ideally, such areas should be designed so that the crack extends into a low stress area so that its propagation becomes slow. It is possible to calculate, using statistics and the observed rate of cracking, an optimum survey periodicity to minimise risk which is indeed done for some offshore structures as described by Madsen et al (1987); such precision is inappropriate for warships which are only accessible for survey at prescribed times. Survey intervals for warships are, in fact, tied to refit or repair period frequency which is usually three to six years. Six years is, however, too long for a conventional structure to be allowed to continue without inspection and arrangements should be made for hull surveys at intermediate stages. About every three years should be the aim for survey periodicity in a conventional vessel.

7 At refit a full survey should be carried out, which must include *all* the structure of the ship, and each compartment or area should be separately reported so that a comprehensive picture of the material state of the ship can be built up and reliably maintained. Reliability of records is of extreme importance so that any decisions on emergency repairs after an accident can be made with confidence, and also so that firm work packages can be prepared for the next repair period. For intermediate surveys it is usually unrealistic to expect the whole structure to be inspected because of the need to take down lagging for access and so on. However, it should be mandatory that all potentially defective areas for that ship and class are inspected as well as all wet spaces and the primary structure. Such a survey will be a burden on the repair authority but the designer should do his best to ensure that it is carried out in a professional manner. Records should state what compartments have *not* been inspected as well as reporting on those that have so that action can be taken to complete the survey at the first possible opportunity, which may not be at a normal repair period.

8 Good instructions for survey of warships are contained in Upkeep and Support Policy Document No. 7, 'Hull Survey of Surface Ships', published by the Ship Refitting Department of the MOD. Generally, the survey of structure will be visual with ultrasonic thickness testing being used in critical areas such as the outer bottom and the upper deck, and any other parts about which the surveyor has doubts. A chipping hammer is also a valuable tool for the surveyor for removing paint and rust in suspect areas so as to establish the extent of deterioration. The surveyor should not be inhibited about chipping away paint because if it is loose corrosion will be progressing underneath anyway and if it sound little damage will be done. However, any exposed metal should be correctly preserved afterwards.

9 Where defects are found during survey, even if they appear to be relatively insignificant, they should always be repaired unless the surveyor is convinced that they will not affect safety or operational capability before the next repair period. Shortage of resources will rarely be an acceptable excuse for not carrying out a repair. The hull is the most important part of a vessel and unless it remains reliable the effectiveness of all the systems and equipment becomes suspect.

10 Requirements for repair of warships are laid down in NES155 Part 2, but the principle must always be to remove damaged material and replace it with new. Doubler plates are never very effective and only serve to cover up defects, making them more difficult to survey and allowing corrosion or fatigue cracks to progress under cover. When replacing fatigue damaged material it is important to remove enough to ensure that cracking does not start again quickly at the boundary of the insert. This requires some knowledge of the stress pattern so that all highly stressed material can be removed. It should also be remembered that the crack will itself have modified the stress pattern and so a greater area of material may need to be removed than might be supposed from the intact structure. Note that unless the original structure is known to be seriously deficient, there is little to be gained from replacing old material with new that is thicker or of higher strength. The actual stress pattern will not be much affected as it is dependent on the overall strain in adjacent structure, and neither fatigue nor corrosion is less likely in high strength material.

11 If defects are reported in service when there is no opportunity to complete a full repair, then they should be exposed and reported on regularly to the design authority by the ship's staff.

The propagation of fatigue cracks can, however, be delayed by drilling out the end of the crack (note that the *true* end should be drilled out which may not be the visible end, and some form of non-destructive examination may be desirable) and inserting a bolt of diameter equal to the plate thickness or a little more. This bolt should be torqued up until it is almost yielded. The resulting compression in the plate can slow crack propagation down to a quarter of the expected rate, as discussed by Hugill and Sumpter (1989(b)).

12 The repair of FRP is a very different process from that of metals and reference should be made to Beale (1989) for details.

13 The necessary extent of repair of distorted or dented structure is less easy to define. The *average* distortion assumed during design (see Chapter 7) is not much affected by a single local displacement that is significantly greater than the average. However, if there is a large area of distortion, perhaps resulting from explosion damage or grounding, then more detailed checks on strength should be carried out using the severe distortion curves given in Chapter 18. Frequently distortion will need to be repaired for other reasons than structural strength, for example because of resulting misalignment, flow disturbance or simply unsightliness. In all cases it is usually better to cut out the distorted material and so replace it; trying to straighten it is never very successful and leads to unwanted residual stresses. If the distortion is small enough to remove easily then it is probably not worth removing at all.

14 It is then clear that the structural surveyor needs to be experienced both in structural performance and design. Not only does the designer need to have a good understanding of how the structure is likely to perform in service, but the surveyor of that structure needs to understand what was intended by the designer; what the general stress pattern was expected to be and what margins were allowed. The alternative would be a non-professional surveyor who would need to report *everything* that departed from the as built state, leaving the design authority to interpret an indigestible mass of data before deciding on necessary repairs. That process would be likely to impose delays which could lead to important work being omitted from the current work package, and possibly requiring operational restrictions at a later date.

Design Matters

15 The foregoing paragraphs have described briefly the processes of deterioration of a ship's structure and the means of surveying and slowing, if not arresting, that deterioration. There are many things a designer can do both to reduce the incidence of damage in service and to assist the surveyor and maintainer to keep the structure to an acceptable standard. If, in addition, a structure is easy to maintain it will also be easier, and therefore cheaper, to build.

16 Generally it is better to err on the side of the simple, open structure than move towards a complex and tightly constrained arrangement even though the latter may be lighter in weight. A structure with fewer stiffeners will have fewer welded joints where corrosion can initiate, and heavier scantlings will be less sensitive to corrosion effects. Moreover, if the structure is simple and robust, distortion is less likely to be caused during the construction welding and assembly process, and fit-up of the components will be easier. It follows that the structure will be nearer to the ideal that is implicit in the analytical process and that unexpected local stress concentrations and resulting fatigue damage are less likely to appear.

Corrosion Protection

17 Protection against corrosion is usually by means of paints or similar coatings and therefore good access as described above is essential if the paint is to be properly applied. Good access is also required for inspection of preservative coatings, as corrosion beneath a coating is common and if it allowed to progress unchecked because it is not immediately visible then severe damage can occur. Corrosion beneath floor coverings and bulkhead and deckhead linings is a particular hazard especially in wet spaces such as bathrooms and in some passageways, and wherever acceptable such coverings should be avoided in favour of bare or painted steel.

18 Another important aspect is drainage both of external decks and internally in wet spaces. Generally exposed decks are cambered so that as long as the ship is reasonably upright water will drain to the ship's side. However, if spurnwaters are fitted water may still lie near the deck edge and frequent drain holes or scuppers through the spurnwater are essential as described for warships in NES115. Further, if the spurnwater is of wood and bolted to the deck then water can lie in the interface between the steel deck and wood causing accelerated corrosion in that area. From the structural point of view it is better not to fit spurnwaters or solid bulwarks, but to allow water to drain freely. If a spurnwater is fitted it should be integrated with the structure and be of the same material.

19 If decks are not cambered, scuppers should be fitted at the inboard side of exposed decks against deckhouse sides, as well as at the deck edge, as water will lie on one side or the other of the ship however upright it is. Such scuppers should be as frequent as the deck edge drainage spaces in the spurnwater.

20 The flatness of decks is also important and the standards laid down for warships in NES147 should be achieved to minimise the amount of water that will lie on deck in the depressions between stiffeners. Corrosion is especially likely in such areas if they are inaccessible under upper deck equipment or non-slip deck coverings and cannot be readily kept dry. Passageways are particularly vulnerable to corrosion along the edges and up the lower boundary of adjacent bulkheads, where any deterioration can seriously affect the resistance of the structure to internal blast.

21 Inside the ship good drainage in the form of scuppers is essential in all wet compartments. Scuppers should be positioned at diagonally opposite corners of a rectangular space and in all places where water may built up in spaces of more complex shape. In tanks or compartments against the bottom of the ship where scuppers are inappropriate, pumping arrangements should be such that a minimum of water lies in the bottom when the space is not in use, and that the whole space is easily accessible for cleaning and preservation.

22 In compartments against the ship's side, and especially in hot or humid spaces, as in some machinery spaces, condensation can form if the lagging is inadequate or damaged, or indeed if there is no insulation. In these places the condensation will collect on the upper side of longitudinal stiffeners and extensive corrosion can be caused. It is rarely possible to arrange longitudinal stiffeners in the side to be self draining and so it will be necessary to cut drainage holes, sometimes known as 'rat-holes', in the webs of the stiffeners. If these holes are not cut carefully in accordance with requirements similar to those for warships in NES155 Part 1 and NES706, and the cut edge properly dressed clean and smooth, then they themselves can act as both an initiation point for fatigue cracking and for corrosion because they will be difficult to preserve properly. It is also important that the ship's side is accessible for inspection and repair where such corrosion damage is possible. Allowance should be made for such access when siting items of machinery.

Fatigue Resistant Structure

23 Stress concentrations leading potentially to fatigue damage will occur at any point in the structure where a load has to be turned through an angle, such as at the end of a superstructure or in a cranked plate or stiffener, or where the load is compressed into a smaller volume of material, such as around holes in structure or where structure reduces in thickness. Ideally, all such changes would be designed to occur gradually but such perfection can only be achieved at great cost in special items whose integrity is essential, for example turbine blades. For ship structure the designer has to manage with discrete sizes of plates and stiffeners as well as step changes in the structural arrangements resulting from essential layout considerations. All design to reduce the risk of fatigue failure is therefore a compromise between many conflicting pressures.

24 Some advice on the siting and arrangement of holes is given in Chapter 6 for decks and in Chapter 9 for bulkheads, and in general terms for the design of coamings and compensating structure in Chapter 12. The principle should be to site holes in areas of low stress if possible so that stress concentrations at their corners still lead to acceptably low stresses. This includes siting small holes in the 'shadow area' of larger holes as shown in Figure 12.4. However, the most important aspect to achieve is that *all* holes, whether large or small, in major or minor structure, should have radiussed corners in accordance with the requirements for warships in NES155 Part 1. Furthermore, no weld run should end at the corner of a hole or within the vicinity of it because the resistance of the weld metal and the heat affected zone to fatigue is always less than the parent plate. Ideally, all welds should be in plane plate or stiffener subject only to the mean field stresses. It must be remembered that cracking in minor structure can affect the efficient operation of the ship or crew as much as in major structure and will need just as much effort to repair.

25 In avoiding fatigue problems at structural discontinuities the most important aspect is to arrange the structure so that the majority of loads are taken in-plane (direct or shear) and not in bending, and that where a change of thickness or scantlings occurs it happens gradually. The first of these requirements means that no structure should ever end in the middle of a plate or panel without continuous support. Examples are the ends of superstructures, which are discussed in Chapter 8, and the stiffeners to bulkheads, discussed in Chapter 9. Additionally, stiffeners or plate should never be cranked without a third member to provide the other 'leg' for a triangle of forces. Where a change of scantlings is inevitable, for example when a plate or stiffener steps down in size, the transition should be tapered in such a way that the slope of the stress change is not steeper than 1:4. For plate that means a taper ground on the edge with a 1:4 slope but for stiffeners the taper may need to be somewhat longer.

26 The above paragraphs include a selection of aspects which the designer must consider when developing the ship's structure, in order to minimise the rate of deterioration. There are many other forms of structural detail which can cause premature corrosion or fatigue damage, for example intermittent welding, acute angles between structural components leading to inaccessibility, or indeed bad combinations of different metals, and the designer must be on the alert at all times to see that such features are avoided.

Material Aspects

27 The use of materials other than steel, as discussed in Chapter 5, may be appropriate to meet particular design requirements, including reduction of the maintenance load. However, some materials may in certain circumstances *increase* the need for maintenance. The principles of good access for survey and preservation apply whatever the material, but the effects of corrosion and fatigue will vary. If aluminium is used then corrosion is of lesser importance although it can still occur, especially due to electrolytic action if the aluminium is in close proximity to steel. However, the main problem with aluminium is its poor fatigue resistance; in general the allowable stresses in aluminium will be less than half those in steel and so very little is gained in weight reduction through the use of aluminium in a cyclically loaded structure.

28 Maintenance of fibre reinforced plastics (FRP) poses somewhat different problems. Neither corrosion nor fatigue is of great significance in marine FRP structures and, except in areas such as fresh water tanks, it is not necessary to coat the material; painting is mainly cosmetic. Consequently, FRP may be a valuable material to substitute for steel where corrosion or fatigue would be particular problems, for example in superstructure as discussed in Chapter 8. Nevertheless, FRP may delaminate under impact or explosive loading or can deteriorate in the presence of some chemicals which may be present accidentally, so it is still important to provide ready access for survey. Indeed, because construction is very labour intensive, good access is needed in all spaces during building.

29 Delamination is the main form of deterioration of FRP and will most likely be seen at boundary angles between decks, bulkheads and the ship's sides, or at the flanges of stiffeners. Delamination of plane laminate is only likely to occur after physical damage from impact of some sort. Non-destructive examination of FRP other than by visual means is difficult to achieve at present except in local areas and so is only practicable where damage is already suspected. Survey is complicated, therefore, if the structure is painted and visual examination is not possible. If delamination is suspected either because of visual damage to the surface or because unusual movement of the structure is apparent, then the paint must be removed so that the structure can be examined closely. To establish the *extent* of delamination when it is suspected, ultrasonic methods may be used. For more details on properties, survey and repair of FRP see Chapter 5, NES752 and Beale (1989).

30 If it is impossible to design a particular part of a ship to be reasonably accessible for survey then the designer should ensure that the probability of corrosion and fatigue is minimised and that the scantlings are such that any deterioration during the expected period between inspections will not affect the safety or reliability of the structure.

Conclusions

31 A clear understanding of the problems of surveying, maintenance and repair is an essential part of design. The structure of a ship is constantly changing in response to its environment and usage and the designer must take account of these changes and allow margins for deterioration which may not be repaired for some time. At the same time he must try to ease the difficulties of the surveyor and repairer by keeping structure simple and accessible. Only by such means will the through life costs of the ship's structure be minimised.